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**Mikado et al.**

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(54) **ACCELERATION SENSOR**

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**ABSTRACT**

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73/514.34; 73/514.16; 310/329; 310/330;  
310/331; 310/332

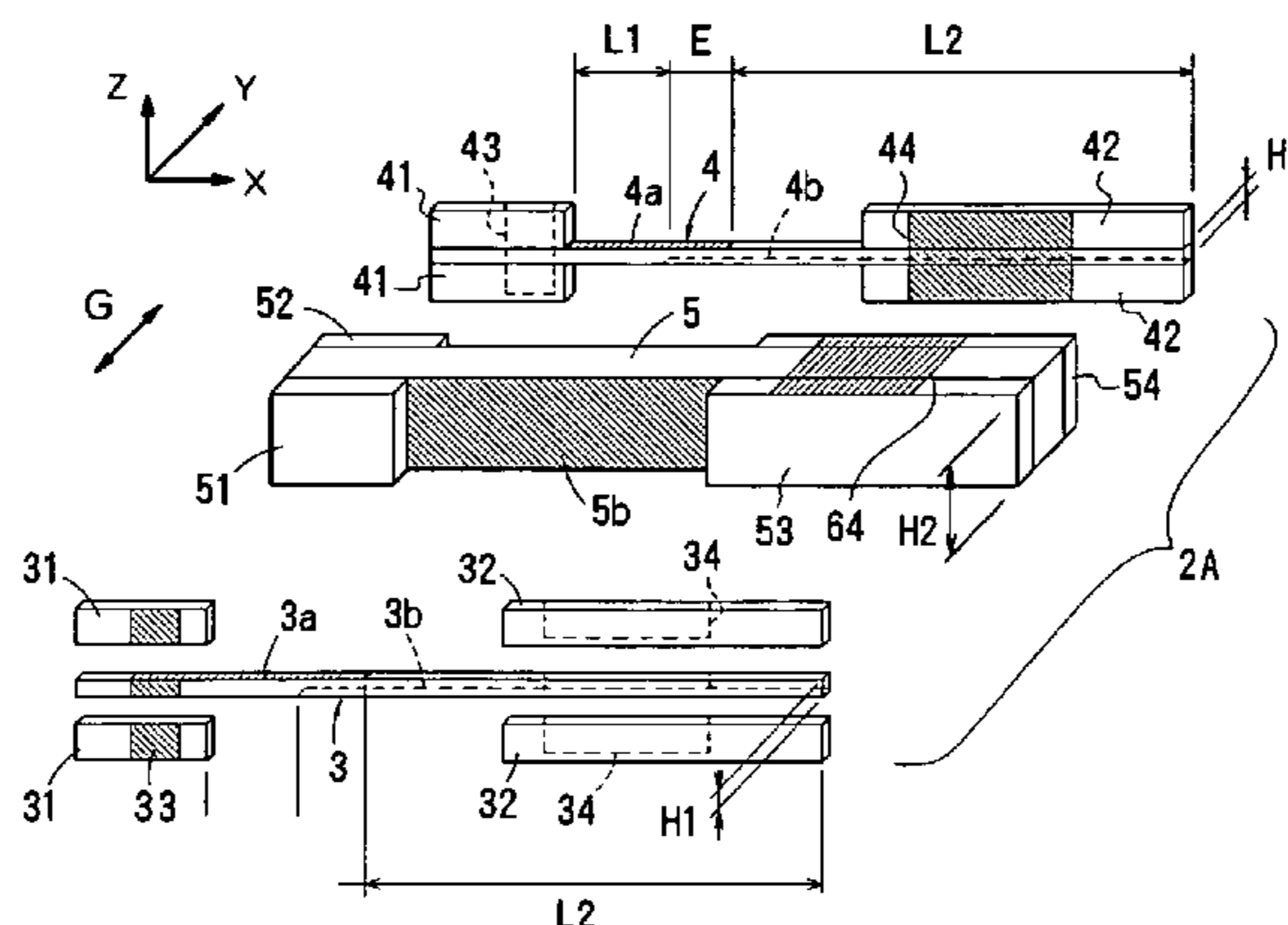
(58) **Field of Classification Search** ..... 73/514.34,  
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See application file for complete search history.

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**7 Claims, 6 Drawing Sheets**



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FIG. 1

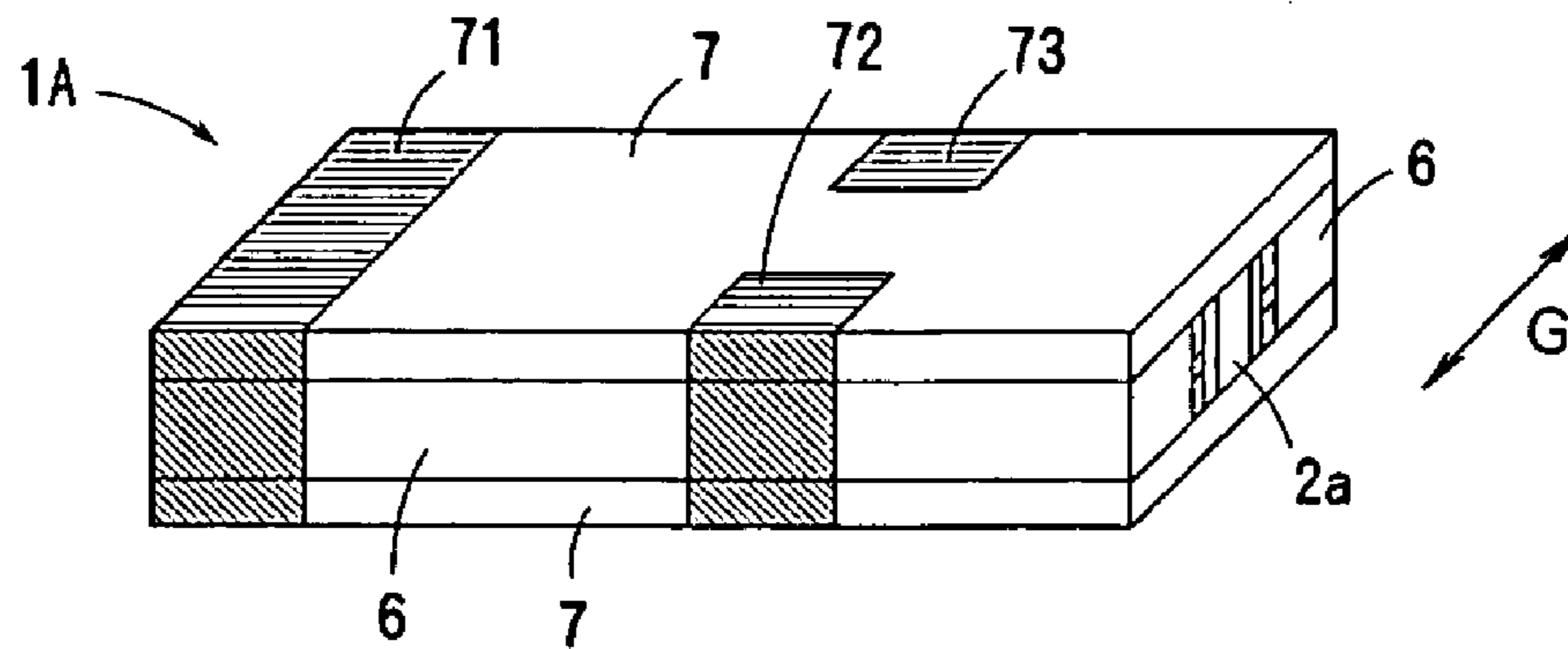
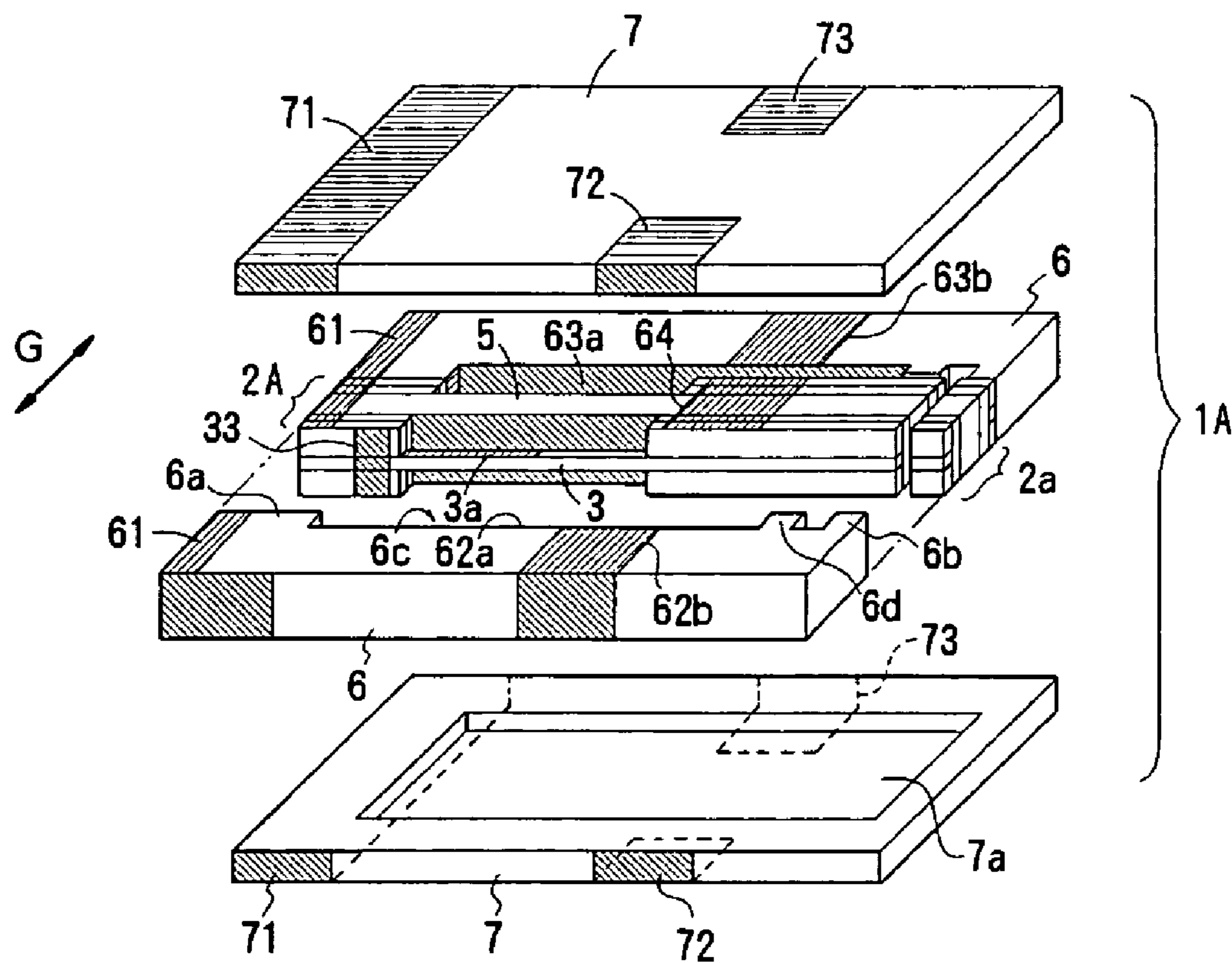
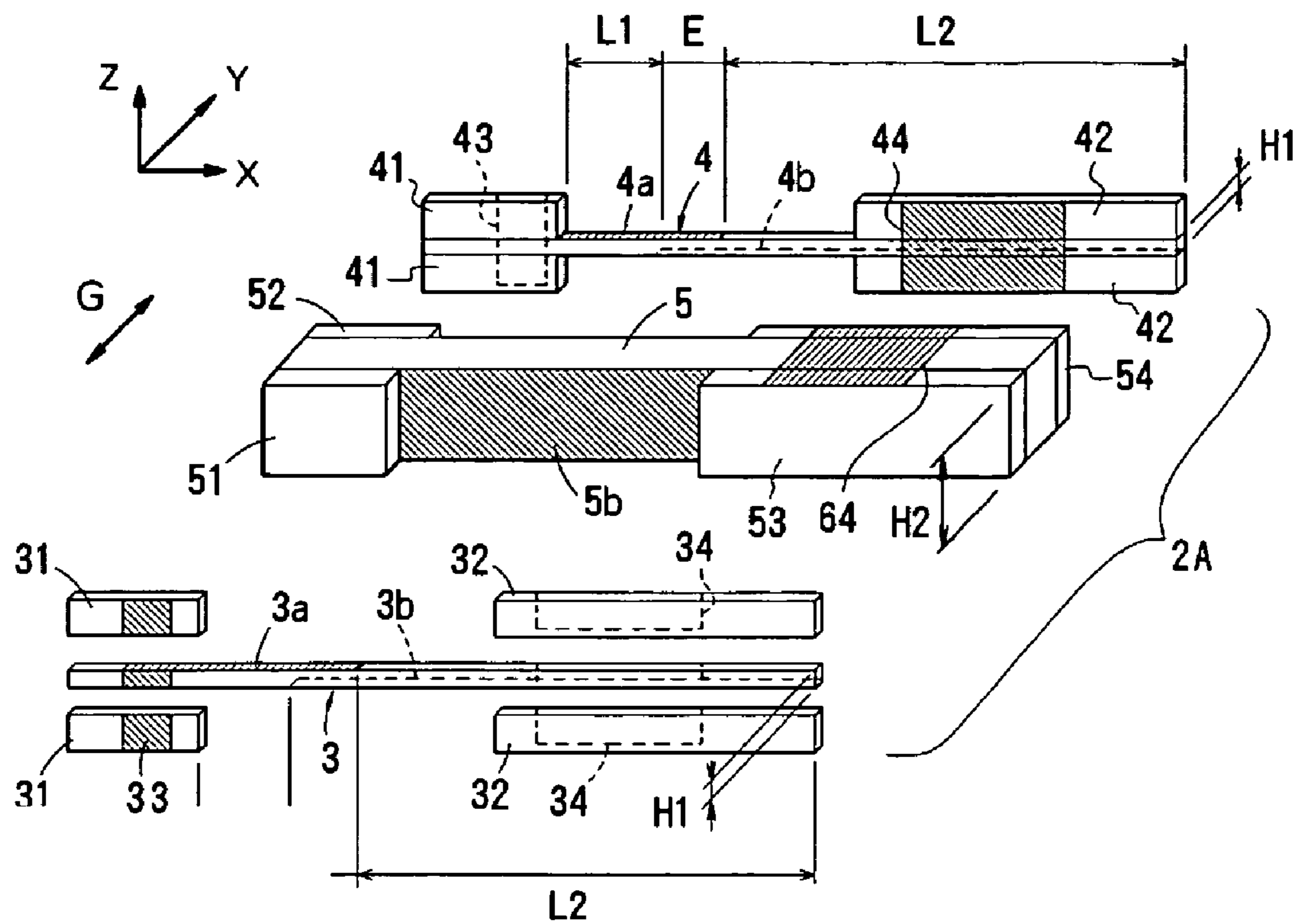


FIG. 2



**FIG. 3**



**FIG. 4**

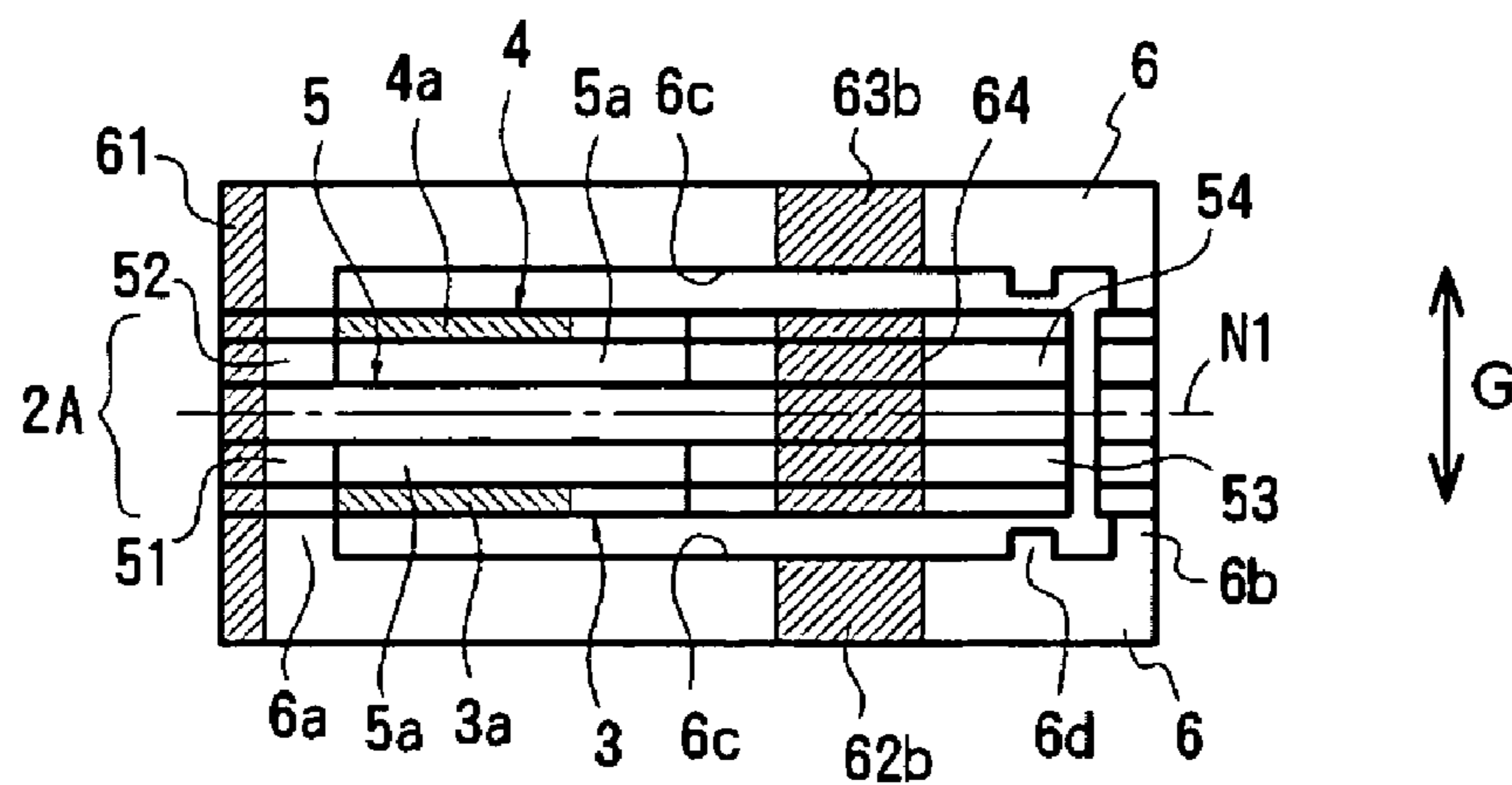


FIG. 5A

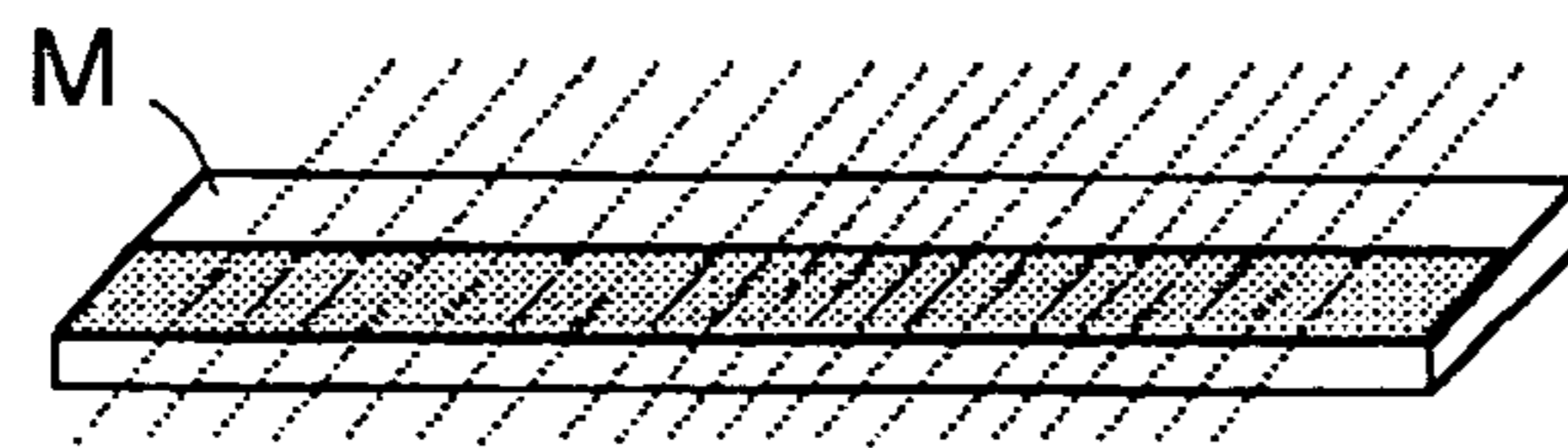


FIG. 5B

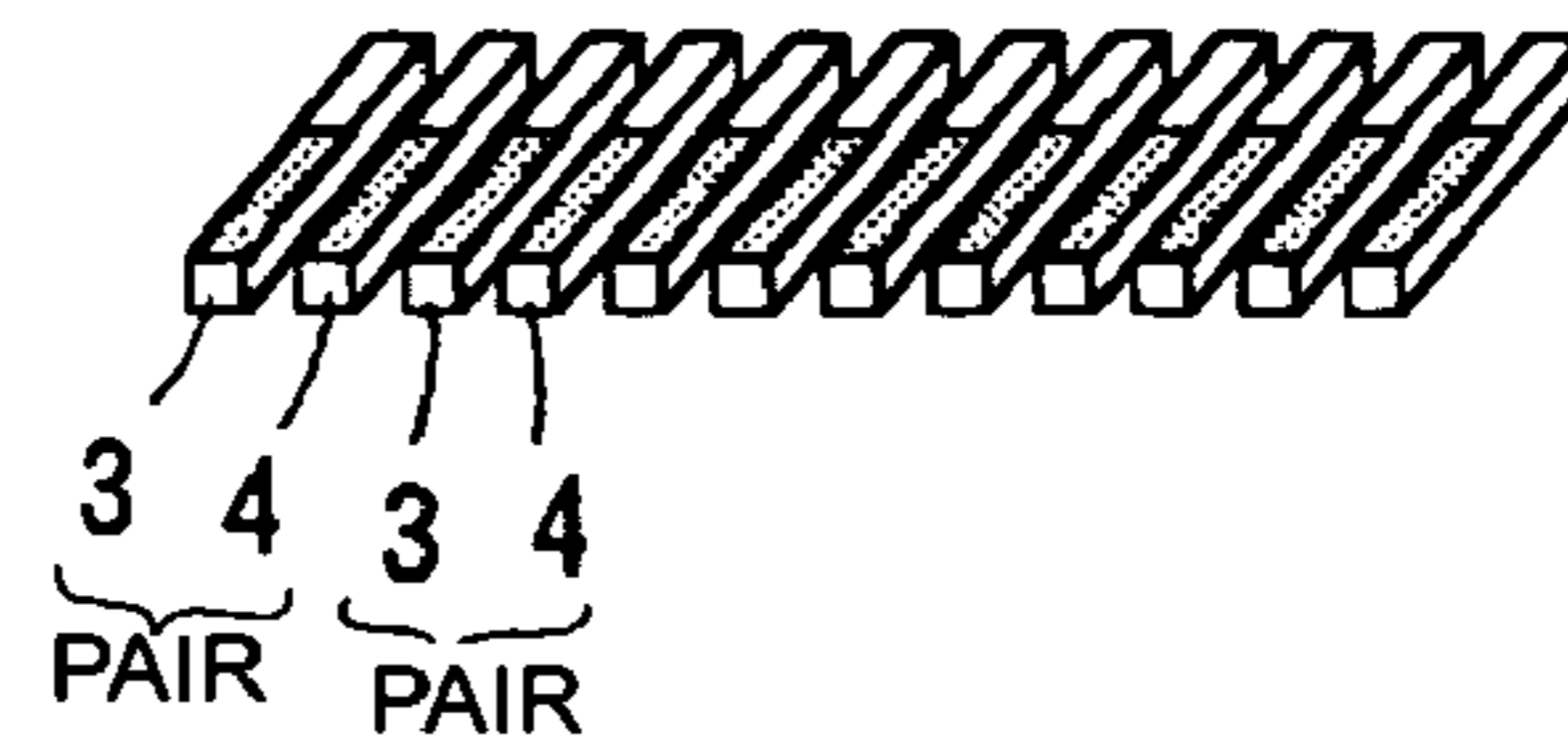


FIG. 6

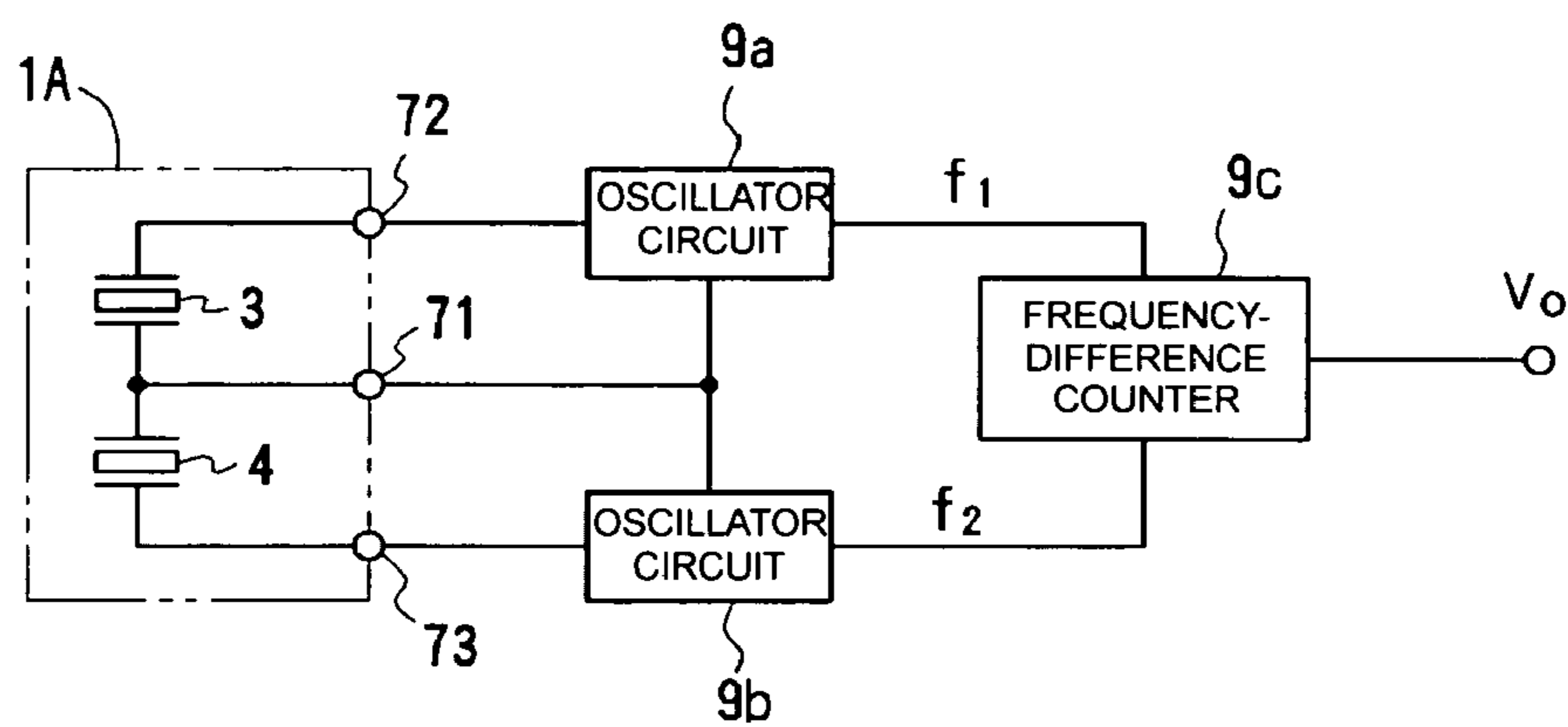


FIG. 7

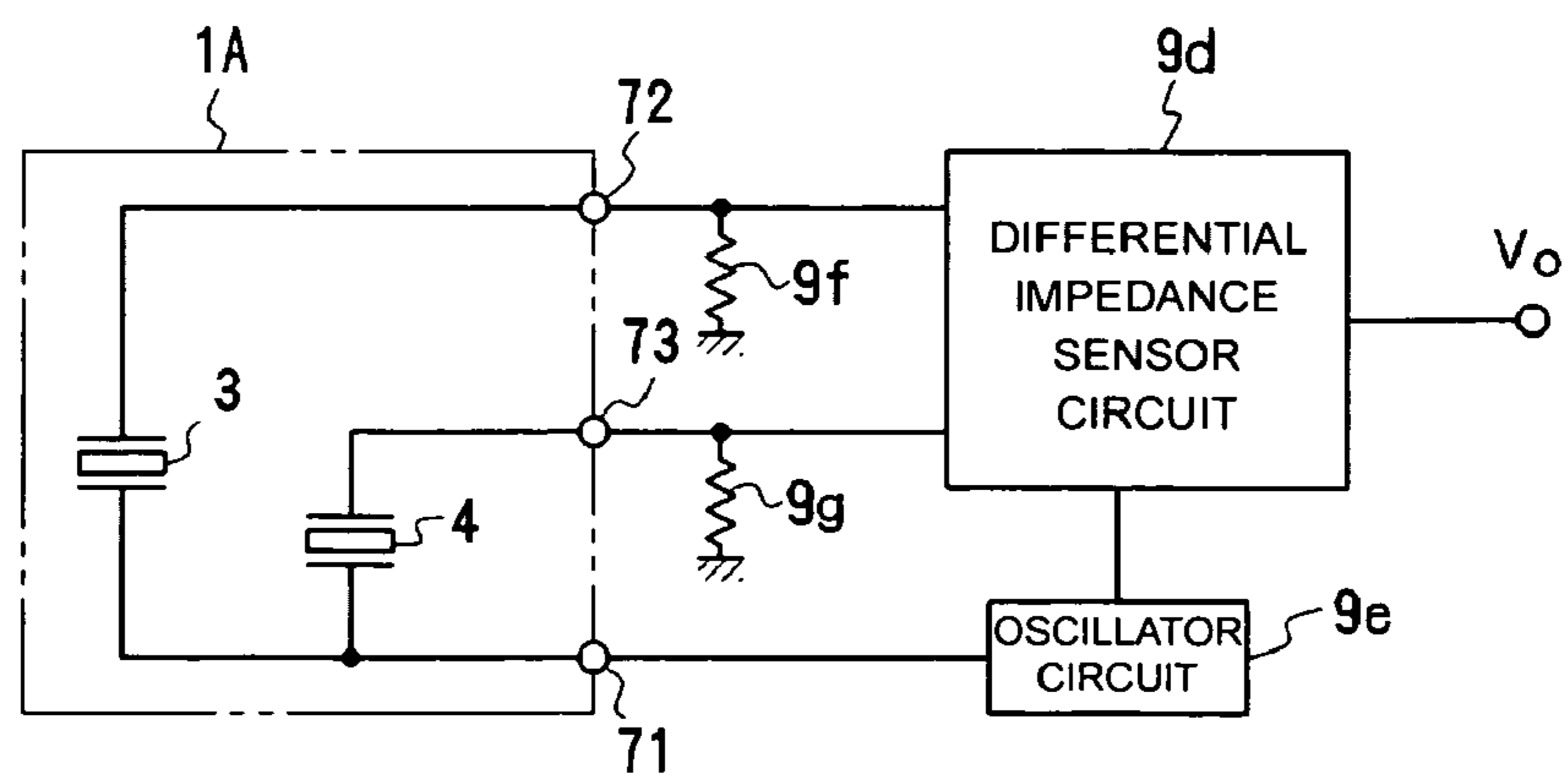


FIG. 8

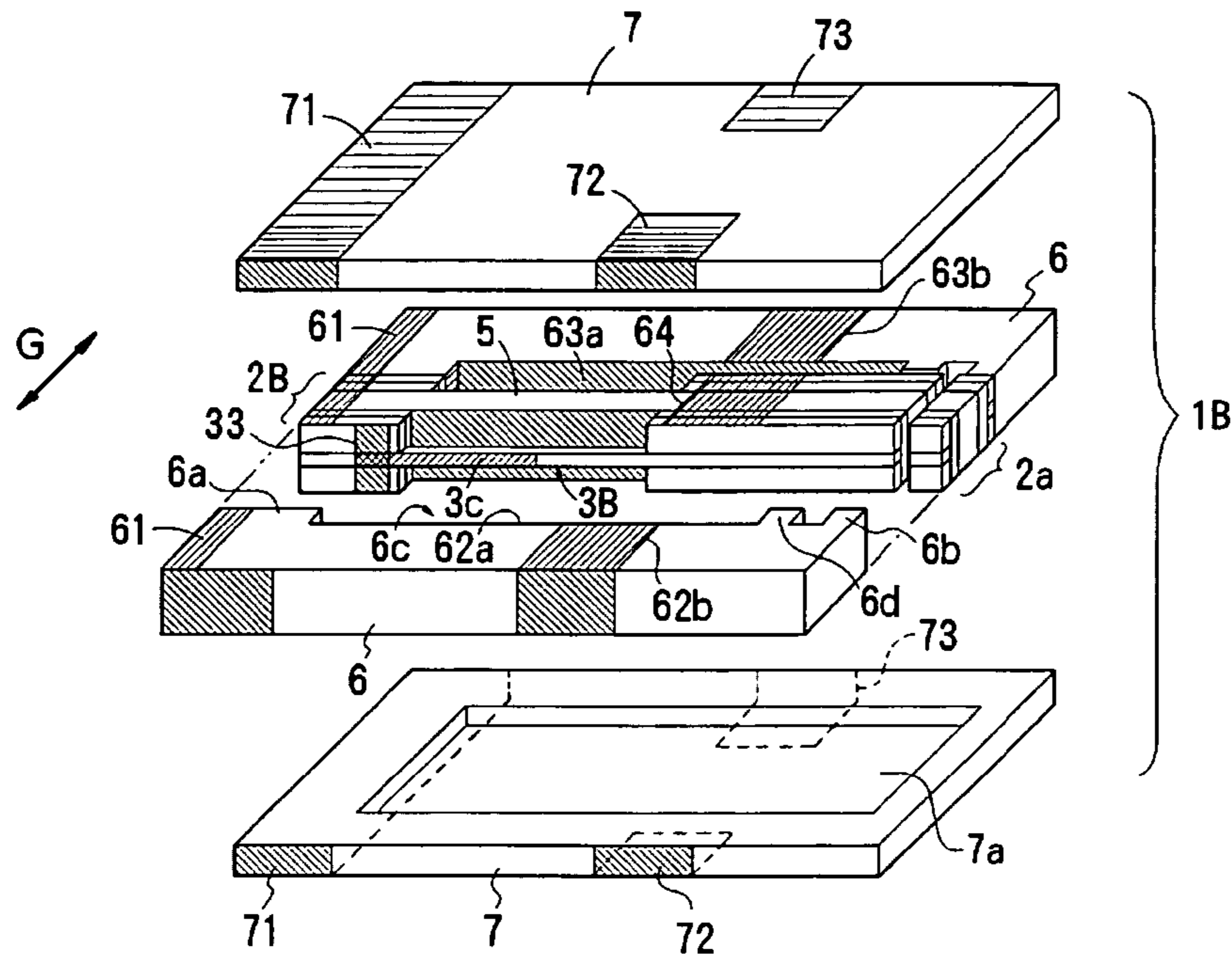
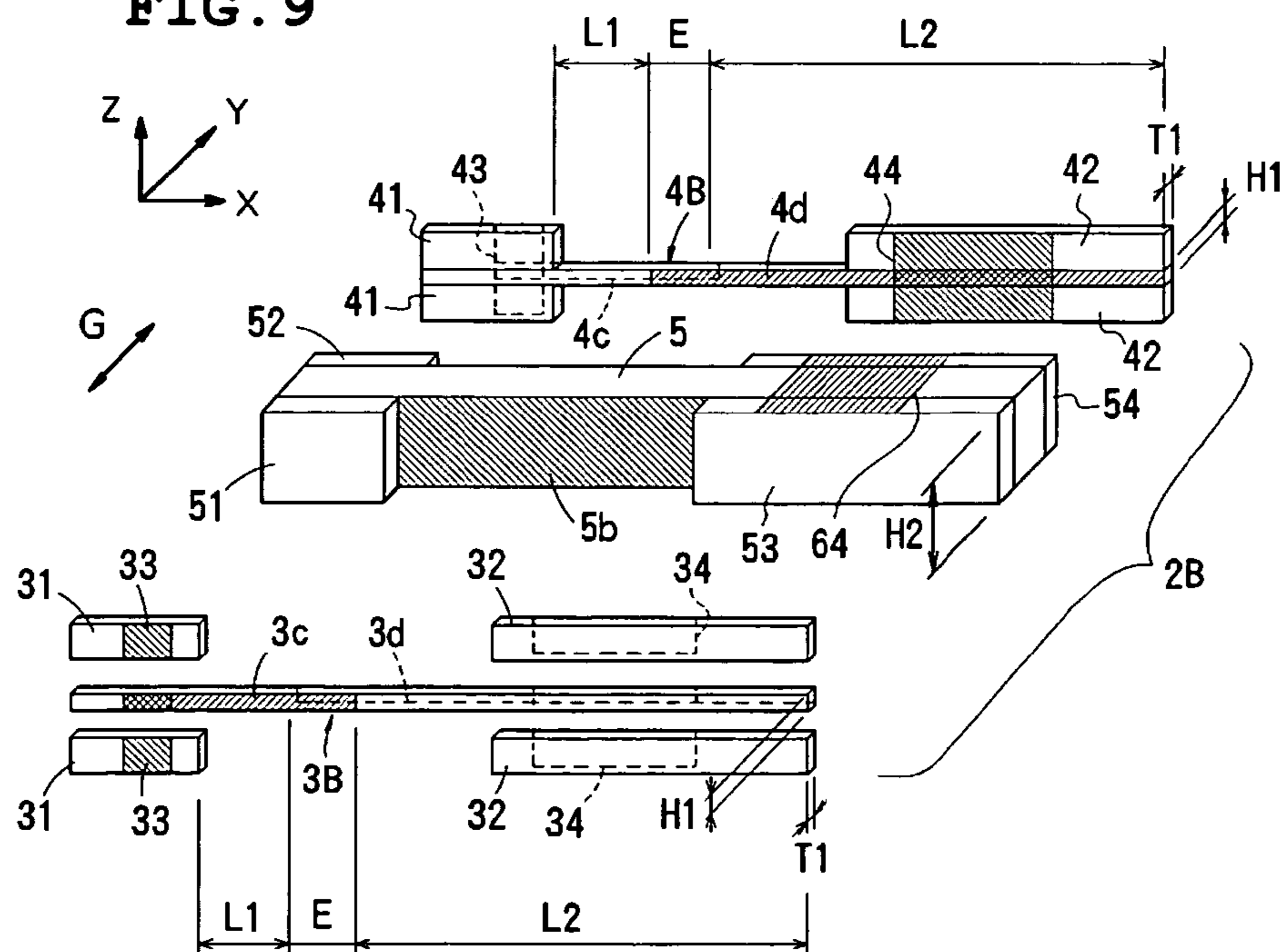
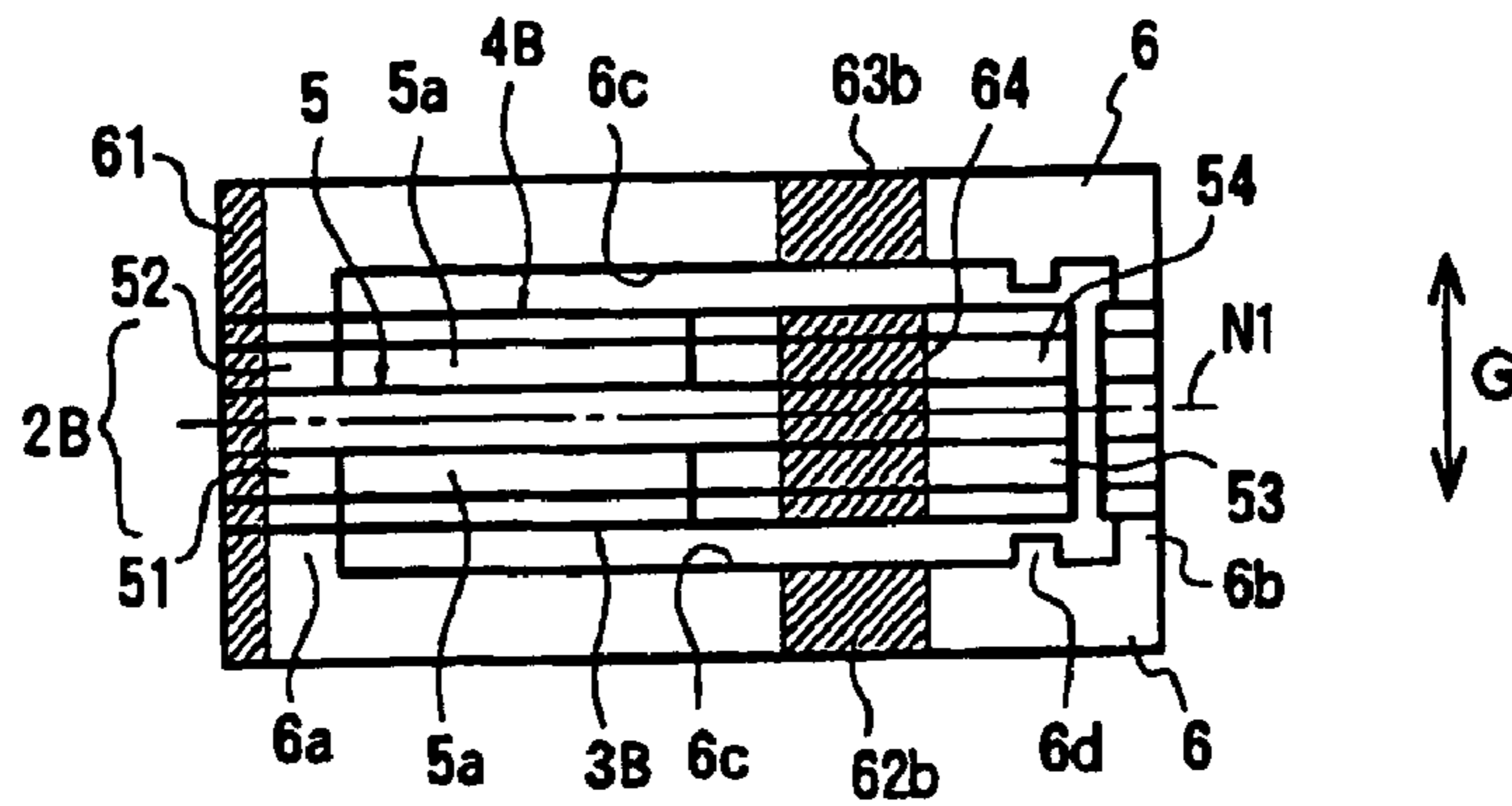


FIG. 9



**FIG. 10**



**FIG. 11**

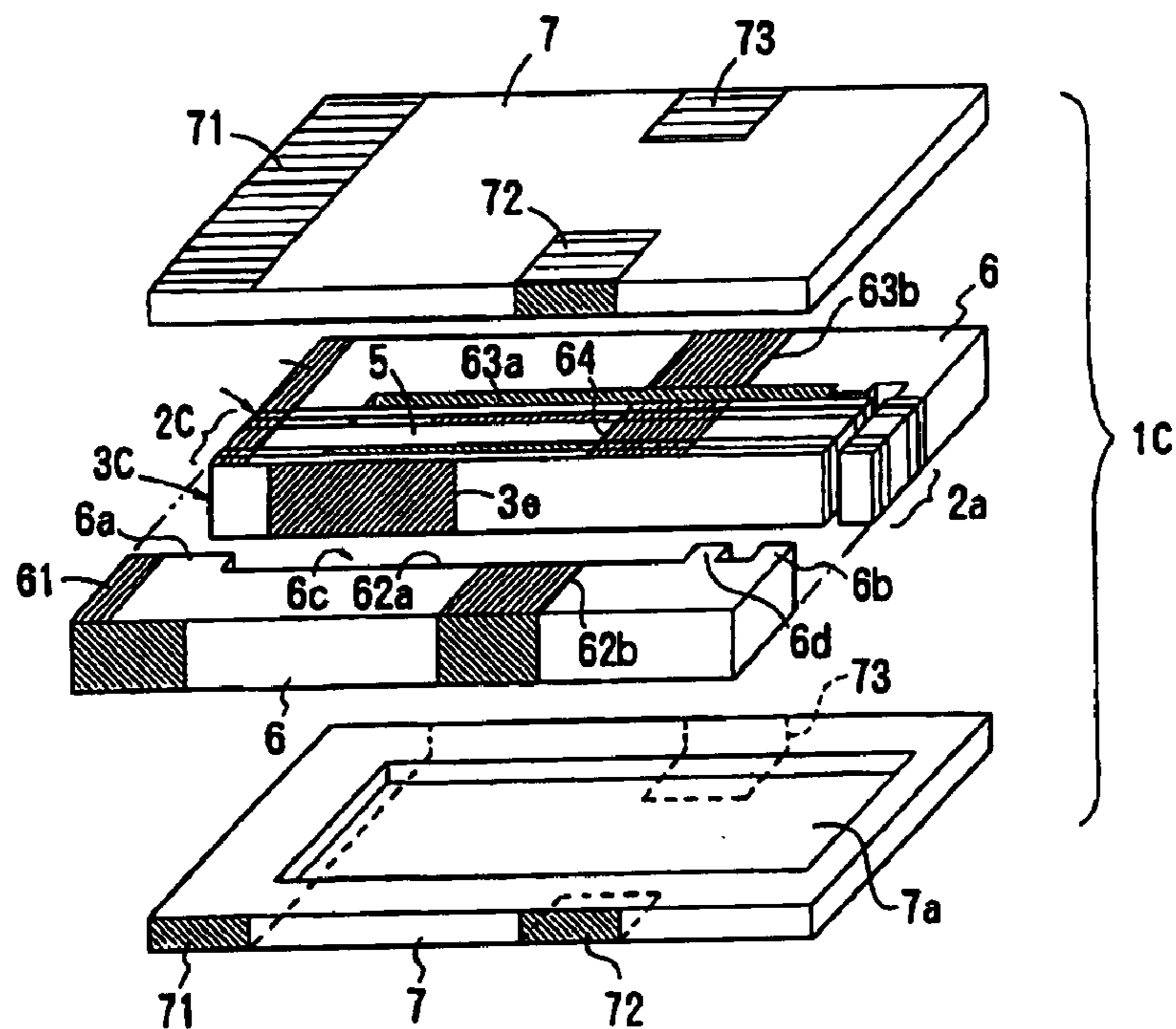
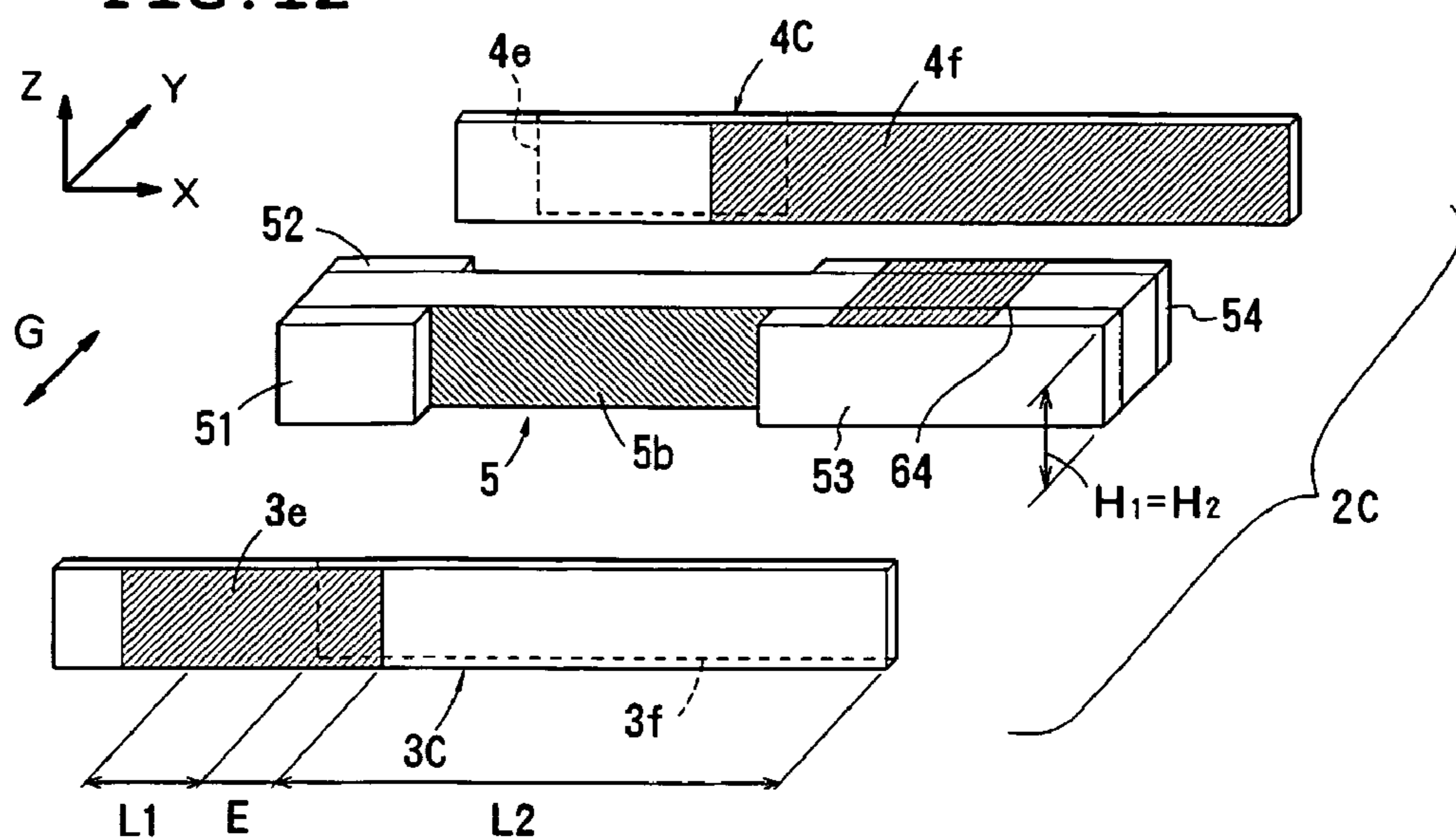


FIG. 12



## 1

## ACCELERATION SENSOR

## BACKGROUND OF THE INVENTION

## 1. Technical Field of the Invention

The present invention relates to acceleration sensors, and particularly, to an acceleration sensor including a piezoelectric material.

## 2. Description of the Related Art

A known acceleration sensor including piezoelectric ceramics is, for example, disclosed in Japanese Patent No. 2780594, hereinafter referred to as Patent Document 1. Such an acceleration sensor is provided with a bimorph sensor element including a pair of piezoelectric units which are composed of piezoelectric ceramics and are integrally joined to each other in an opposing manner. The sensor element is held inside a casing in a double-supported fashion. When acceleration is applied to the acceleration sensor, the sensor element bends, thus generating stress in the piezoelectric units. The electric charge or voltage generated due to the piezoelectric effect is then detected in order to determine the acceleration. Acceleration sensors of this type are advantageous in view of their compactness and their capability of being formed easily into surface-mounted units (chip units).

In an acceleration sensor based on the above-described principle, a bias current flowing from a circuit is stored in a capacitor C of the piezoelectric material. In order to prevent the circuit from becoming saturated, a resistor R is required for allowing the bias current to be released. However, since the resistor R and the capacitor C define a high pass filter, the acceleration in the frequencies below the cut-off level, such as DC and low frequency, cannot be detected.

On the other hand, an acceleration sensor disclosed in Japanese Unexamined Patent Application Publication No. 2002-107372, hereinafter referred to as Patent Document 2, particularly, the acceleration sensor shown in FIG. 8 in Patent Document 2, includes a single base plate whose opposite sides respectively have first and second resonators formed of a piezoelectric material attached thereto so as to form an acceleration-sensor element, each of the first and second resonators having electrodes on opposite sides thereof. One longitudinal end or both longitudinal ends of the acceleration-sensor element is/are fixed such that the first and second resonators are bendable in their opposing direction in response to acceleration. When the acceleration-sensor element bends in response to the acceleration, changes in frequency or changes in impedance in the first and second resonators caused by the bending of the acceleration-sensor element are differentially detected in order to detect the acceleration.

In this case, the acceleration in a DC or low-frequency level can be detected. Moreover, the changes in frequency or the changes in impedance in the two resonators are differentially detected instead of being detected in a separate manner. This counterbalances the stress (for example, a stress caused by a change in temperature) applied to both resonators. Thus, a high-sensitivity acceleration sensor, which is unaffected by, for example, a change in temperature, is achieved. Furthermore, because the central bending plane (i.e., a plane where stress is 0) is set in the base plate, a large degree of tensile stress and compressive stress can be generated in the resonators disposed on the opposite sides of the base plate. Accordingly, this improves the sensitivity of the sensor.

Generally, in view of sensitivity, an acceleration sensor having one longitudinal end of the acceleration-sensor element fixed in a cantilever manner is advantageous to an

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acceleration sensor having both longitudinal ends fixed in a double-supported manner. However, in these acceleration sensors, the vibrating section in each of the first and second resonators is positioned at the central portion of the resonator with respect to the longitudinal direction thereof. For this reason, signals generated in the first and second resonators in response to the acceleration cannot always be detected efficiently, thus inhibiting higher sensitivity (S/N ratio) of the sensor.

## SUMMARY OF THE INVENTION

In order to overcome the problems described above, preferred embodiments of the present invention provide a compact, high-sensitivity acceleration sensor that is not affected by factors other than acceleration, such as a change in temperature or other factors.

According to a preferred embodiment of the present invention, an acceleration sensor includes a base plate, and first and second resonators each formed of a piezoelectric material and each having electrodes on two opposite main surfaces thereof, each resonator having a vibrating section at an intermediate portion of the resonator with respect to the longitudinal direction thereof. The first and second resonators are attached to opposite sides of the base plate with respect to a direction in which acceleration is applied so as to define a bimorph acceleration-sensor element, wherein one longitudinal end of the acceleration-sensor element is fixed such that the first and second resonators bend in the same direction in response to the acceleration, and wherein changes in frequency or changes in impedance in the first and second resonators caused by the bending of the acceleration-sensor element are differentially detected in order to detect the acceleration. The acceleration-sensor element is bendable about a central bending plane in response to the acceleration, the central bending plane being positioned at a central portion of the base plate with respect to the application direction of acceleration. The vibrating section in each of the first and second resonators is disposed close to the fixed end of the acceleration-sensor element.

According to a preferred embodiment of the present invention, the acceleration-sensor element has a bimorph structure in which the resonators are attached to the opposite sides of the single base plate, and the central bending plane is positioned at the central portion of the base plate with respect to the thickness of the base plate. Consequently, when acceleration is applied to the acceleration-sensor element, the base plate functions as a mass body so as to effectively generate a tensile stress in one resonator and a compressive stress in the other resonator. In a certain vibration mode, the frequency in the resonator with tensile stress decreases while the frequency in the resonator with compressive stress increases. By differentially detecting the changes in frequency or the changes in impedance in the resonators, the acceleration can be detected. Moreover, since the changes in frequency or the changes in impedance in the two resonators are detected in a differential manner, the stress applied to both resonators (for example, a stress caused by a change in temperature) can be counterbalanced. Accordingly, a high-sensitivity acceleration sensor that is unaffected by, for example, a temperature change is provided.

In a preferred embodiment of the present invention, the vibrating section in each of the first and second resonators of the acceleration-sensor element with a cantilever structure is positioned close to the fixed end of the acceleration-sensor element. In such an acceleration-sensor element with a

cantilever structure, the stress generated in the first and second resonators in response to acceleration is greater towards the base-end portion. By placing the vibrating section of each resonator closer to the base-end portion to an extent such that the vibration is not interfered, a signal can be detected from the base-end portion of the resonator, which is the position where the largest degree of stress is present. Accordingly, this achieves higher sensitivity (S/N ratio) of the sensor.

There are, for example, two approaches for obtaining a signal proportional to the acceleration acting upon the acceleration-sensor element based on the signals differentially detected from the two resonators. One approach is to oscillate the first and second resonators separately with different frequencies, determine the oscillating-frequency difference, and obtain the signal proportional to the acceleration based on the frequency difference. The other approach is to oscillate the first and second resonators with the same frequency, detect the phase difference or the oscillation difference based on the difference in electric impedance between the resonators, and obtain the signal proportional to the acceleration based on the phase difference or the oscillation difference.

Furthermore, a height of the first and second resonators in a direction that is substantially perpendicular to the application direction of acceleration is preferably smaller than a height of the base plate in the direction that is substantially perpendicular to the application direction of acceleration.

Specifically, by reducing the cross-sectional area of the first and second resonators, the tensile stress and the compressive stress generated in the resonators in response to acceleration are increased, thus further improving the sensitivity (S/N ratio).

Furthermore, the first and second resonators are preferably attached to the opposite sides of the base plate at positions where the first and second resonators are opposed to each other.

Although it is possible to attach the two resonators to the opposite sides of the base plate at positions where the two resonators do not oppose each other, such a structure may lead to detection errors. In detail, this is due to the fact that if the acceleration-sensor element bends in response to an external force from a direction other than the application direction of acceleration (off-axis bending), the two resonators may generate different signals. In contrast, by attaching the two resonators to the opposite sides of the base plate at positions where the two resonators are opposed to each other, signals can be detected from the two resonators in a differential manner. Thus, the difference in detection with respect to the off-axis bending can be compensated for.

Furthermore, each of the first and second resonators is preferably attached to a central portion of the base plate with respect to a height direction of the base plate, the height direction being substantially perpendicular to the application direction of acceleration.

Consequently, in addition to being attached to the opposite sides of the base plate at positions where the two resonators are opposed to each other, each resonator may be attached to the central portion of the base plate with respect to the height direction. This structure can further compensate for the difference in detection since no stress acts upon the two resonators in response to off-axis bending.

Furthermore, the base plate and the first and second resonators are preferably formed of at least one material having substantially the same coefficient of thermal expansion.

If the coefficient of thermal expansion differs significantly between the base plate and the first and second resonators, a tensile stress or a compressive stress may be generated in the resonators due to a change in temperature in the environment even when no acceleration is applied. This leads to changes in frequency or changes in impedance. By allowing the base plate and the first and second resonators to have substantially the same coefficient of thermal expansion, the temperature drift related to the output from the sensor can be prevented, thus reducing thermal hysteresis.

The base plate and the first and second resonators may be formed of the same material, or may be formed of different materials. The coefficient of thermal expansion between the base plate and the resonators may be different to an extent such that the changes in frequency or the changes in impedance in the resonators in an operating temperature limit are within an error range and are thus significantly small.

Furthermore, opposite outer surfaces of the acceleration-sensor element may be respectively fixedly supported by a pair of casing components at the longitudinal end of the acceleration-sensor element, the outer surfaces being opposite to each other with respect to the application direction of acceleration. Moreover, open planes defined by the acceleration-sensor element and the casing components are covered with a pair of cover components so that a displacement portion of the acceleration-sensor element, which is bendable in response to the acceleration, is disposed within an enclosed space. Such a packaged structure allows the displacement portion to be blocked from the outside, whereby a surface-mounted unit that is prevented from being affected by, for example, moisture and dust is provided.

Furthermore, one of the electrodes in each of the first and second resonators is preferably disposed at a free-end side of the resonator and is preferably connected with a common electrode via an extraction electrode provided on the base plate, the common electrode being provided at a fixed-end side of an outer surface of a combination of the casing components and the cover components. Moreover, the other electrode in the first resonator is preferably disposed at a base-end side of the first resonator, the electrode being connected with a first independent electrode provided at a free-end side of the outer surface of the combination of the casing components and the cover components, the electrode being connected with the first independent electrode via a first extraction electrode provided on one of the casing components. The other electrode in the second resonator is preferably disposed at a base-end side of the second resonator, the electrode being connected with a second independent electrode provided at the free-end side of the outer surface of the combination of the casing components and the cover components, the electrode being connected with the second independent electrode via a second extraction electrode provided on the other casing component.

When using an acceleration-sensor element of a cantilever structure, three electrodes are concentrated at the base-end portion of the acceleration-sensor element, and for this reason, it is difficult to set these electrodes distant from one another on the outer surface of the package. In order to set the three external electrodes distant from one another, one pair of the electrodes from the two resonators is connected to the common electrode, provided at the fixed-end side of the outer surface of the package (the combination of the casing components and the cover components), via the base plate, and the other pair of the two remaining electrodes is respectively connected to two independent electrodes, provided at a side of the outer surface opposite to the fixed-end side of the package, via the casing components. Accordingly,

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when used as a surface-mounted unit, a short circuit is prevented from occurring among the electrodes.

Furthermore, the casing components are preferably provided with a plurality of internal electrodes disposed on upper surfaces of the casing components, the internal electrodes being connected with the electrodes in each of the first and second resonators.

In this case, the characteristics of the resonators can be measured easily by allowing measuring terminals to come into contact with the internal electrodes disposed on the upper surfaces of the casing components.

Accordingly, preferred embodiments of the present invention provide an acceleration-sensor element having a bimorph structure in which resonators are attached to opposite sides of a base plate. When acceleration is applied to the acceleration-sensor element, changes in frequency or changes in impedance in the resonators are detected in a differential manner. Accordingly, a high-sensitivity acceleration sensor that is unaffected by, for example, a temperature change is provided.

Furthermore, the acceleration-sensor element has a cantilever structure, and the vibrating section in each of first and second resonators is disposed close to a fixed end of the acceleration-sensor element. Thus, a signal can be detected from near the base-end portion, which is where a large stress is present. This contributes to high sensitivity of the sensor and thus improves the S/N ratio.

These and other features, elements, characteristics and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments with reference to the attached drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic perspective view of an acceleration sensor according to a first preferred embodiment of the present invention.

FIG. 2 is an exploded perspective view of the acceleration sensor shown in FIG. 1.

FIG. 3 is an exploded perspective view of an acceleration-sensor element provided in the acceleration sensor shown in FIG. 1.

FIG. 4 is a plan view of the acceleration sensor shown in FIG. 1 in a state where cover components of the acceleration sensor are removed.

FIG. 5 includes perspective views illustrating a method for cutting a master substrate into segments in order to form resonators.

FIG. 6 is a circuit diagram of an example of an acceleration sensor device provided with the acceleration sensor according to a preferred embodiment of the present invention.

FIG. 7 is circuit diagram of another example of an acceleration sensor device provided with the acceleration sensor according to a preferred embodiment of the present invention.

FIG. 8 is an exploded perspective view of an acceleration sensor according to a second preferred embodiment of the present invention.

FIG. 9 is an exploded perspective view of the acceleration sensor shown in FIG. 8 in a state where cover components of the acceleration sensor are removed.

FIG. 10 is a plan view of the acceleration sensor shown in FIG. 8 in a state where the cover components of the acceleration sensor are removed.

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FIG. 11 is an exploded perspective view of an acceleration sensor according to a third preferred embodiment of the present invention.

FIG. 12 is an exploded perspective view of the acceleration sensor shown in FIG. 11 in a state where cover components of the acceleration sensor are removed.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will now be described.

## First Preferred Embodiment

FIGS. 1 to 5 illustrate an acceleration sensor according to a first preferred embodiment of the present invention.

An acceleration sensor 1A includes a bimorph acceleration-sensor element 2A supported in a cantilever manner by a pair of insulative casing components 6 and a pair of insulative cover components 7 composed of, for example, insulative ceramics. Referring to FIGS. 2 and 3, if the direction in which acceleration  $G$  is applied is defined as the y-axis direction, the longitudinal and height directions of the acceleration-sensor element 2A are defined as the x-axis direction and the z-axis direction, respectively.

The acceleration-sensor element 2A in the first preferred embodiment includes resonators 3 and 4 which are integrally attached to two respective opposite sides of a base plate 5 with respect to the application direction of acceleration (y-axis direction) via corresponding spacers 51 to 54. The resonators 3 and 4 are resonators of an energy-trap thickness-shear vibration type and each include a piezoelectric ceramic plate strip. The resonators 3 and 4 respectively include a pair of electrodes 3a and 3b and a pair of electrodes 4a and 4b. The electrodes 3a and 3b are respectively disposed on upper and lower main surfaces of the piezoelectric ceramic plate strip of the resonator 3, and the electrodes 4a and 4b are respectively disposed on upper and lower main surfaces of the piezoelectric ceramic plate strip of the resonator 4, the main surfaces being substantially parallel to the application direction of acceleration  $G$ . One set of the electrodes 3a and 4a of the resonators 3 and 4 is exposed at the upper side of the acceleration-sensor element 2A, whereas the other set of the electrodes 3b and 4b is exposed at the lower side of the acceleration-sensor element 2A. A first-end portion of the electrode 3a on the upper surface of the resonator 3 is opposed to a second-end portion of the electrode 3b on the lower surface at an intermediate portion of the resonator 3 with respect to the longitudinal direction thereof. Similarly, a first-end portion of the electrode 4a on the upper surface of the resonator 4 is opposed to a second-end portion of the electrode 4b on the lower surface at an intermediate portion of the resonator 4 with respect to the longitudinal direction thereof. On the other hand, the second-end portion of the electrode 3a and the first-end portion of the electrode 3b extend away from each other towards the opposite ends of the resonator 3, and similarly, the second-end portion of the electrode 4a and the first-end portion of the electrode 4b extend away from each other towards the opposite ends of the resonator 4. The resonators 3 and 4 preferably have substantially the same height  $H_1$  in the z-axis direction, and the height  $H_1$  is determined based on the resonance frequency of the resonators 3 and 4. Since the height  $H_1$  of the resonators 3 and 4 is smaller than a height  $H_2$  of the base plate 5 in the z-axis direction, the stress generated in the resonators 3 and 4 due to acceleration applied to the resonators 3 and 4 is greater

than in a case where  $H_1=H_2$ . In the first preferred embodiment,  $H_1$  is preferably set at about  $\frac{1}{3}$  or less of  $H_2$ .

As shown in FIG. 5, the resonators 3 and 4 are preferably formed by cutting a single master piezoelectric substrate M into segments, and pairing adjacent cut segments so as to form pairs of resonators. This reduces the difference in the resonance characteristics including the temperature characteristics between the resonators of each pair. Accordingly, the difference in the output signal between the two resonators, which may be caused by a change in temperature, is reduced so as to achieve an acceleration sensor having less output fluctuation.

Even if the resonators 3 and 4 are a pair of adjacent segments cut from the same master piezoelectric substrate, there still may be cases where the resonance characteristics between the two resonators 3 and 4 are different due to, for example, being attached to the spacers and the base plate 5. Such different characteristics are output as an output signal even when no acceleration is being applied. The set of electrodes 3a and 4a of the respective resonators 3 and 4 is exposed at one side of the acceleration-sensor element 2A, and similarly, the set of electrodes 3b and 4b of the respective resonators 3 and 4 is exposed at the other side of the acceleration-sensor element 2A. Consequently, if the resonance characteristics between the resonators 3 and 4 are different, the electrodes exposed at the upper side or the lower side of the acceleration-sensor element 2A may be trimmed using, for example, laser, or may be coated with, for example, frequency-regulation ink so that the resonance characteristics can be adjusted in order to reduce the difference in the characteristics. Such a trimming process or an ink-coating process is performed after an attachment process of the casing components 6 and a fabrication process of internal electrodes 61, 62b, and 63b (see FIG. 4). In that case, since measuring terminals can come into contact with the three internal electrodes 61, 62b, and 63b disposed on the upper surface of the casing components 6, the trimming process can be performed easily while measuring the characteristics of the resonators 3 and 4. As a result, a high-precision acceleration sensor with less detection error can be provided.

The upper and lower main surfaces of the resonator 3 are provided with spacers 31 and 32 having the same thickness as the resonator 3. The spacers 31 and 32 are fixed adjacent to two respective opposite ends of the resonator 3 with respect to the longitudinal direction of the resonator 3. Similarly, the upper and lower main surfaces of the resonator 4 are provided with spacers 41 and 42 preferably having substantially the same thickness as the resonator 4. The spacers 41 and 42 are fixed adjacent to two respective opposite ends of the resonator 4 with respect to the longitudinal direction of the resonator 4. An area where the electrodes 3a and 3b are opposed to each other and an area where the electrodes 4a and 4b are opposed to each other define vibrating sections E. In detail, each vibrating section E is disposed where the pairs of spacers 31 and 32 or the pairs of spacers 41 and 42 are not disposed. In the first preferred embodiment, the spacers 32 and 42 are disposed adjacent to free ends of the respective resonators 3 and 4 have a greater length than the spacers 31 and 41 disposed adjacent to base ends of the respective resonators 3 and 4. For this reason, as shown in FIG. 3, a distance L2 extending from the vibrating section E of each of the resonators 3 and 4 to the free end of the acceleration-sensor element 2A is longer than a distance L1 extending from the vibrating section E to the base end, i.e. a fixed end, of the acceleration-sensor element 2A, such that each vibrating section E is

disposed close to the fixed end. Because a stress generated in response to acceleration is greater towards the base end of a cantilever structure, providing the vibrating sections E close to the base ends of the resonators 3 and 4 allows the resonators 3 and 4 to receive a greater stress, thus improving the sensitivity of the sensor. The height of the combination of the resonator 3 and the spacers 31 or 32 and the height of the combination of the resonator 4 and the spacers 41 or 42 are equal to the height  $H_2$  of the base plate 5.

Alternatively, the spacers 31, 32, 41, and 42 may be omitted such that the resonators 3 and 4 are directly attached to the two respective opposite sides of the base plate 5.

The resonators 3 and 4 are respectively attached to positions on the two opposite sides of the base plate 5 where the resonators 3 and 4 are opposed to each other, and are most preferably attached to the central portions of the base plate 5 with respect to the height direction of the base plate 5. This is due to the fact that even if the acceleration-sensor element were to bend in response to an external force from a direction other than the direction in which the acceleration is applied (off-axis bending), the difference in detection with respect to the off-axis bending can be compensated for by receiving signals from the two resonators 3 and 4 in a differential manner. The detection difference between the two resonators 3 and 4 opposed to each other is reduced due to the fact that, even in the case of off-axis bending, the same amount of stress acts upon the two resonators. Moreover, attaching the two resonators 3 and 4 to the central positions of the base plate 5 with respect to the height direction of the base plate 5 further reduces the detection difference. Specifically, this is due to the fact that even when stress is generated in the resonators 3 and 4 due to off-axis bending, since each of the resonators 3 and 4 bends with respect to a central bending plane disposed at the central portion thereof in the height direction, the stress is counterbalanced within the resonator 3 or 4.

One side surface of the combination of the resonator 3 and the spacers 31 with respect to the y-axis direction is provided with a connection electrode 33 connected with the electrode 3a of the resonator 3 and extending continuously across the side surface in the height direction (z-axis direction). Similarly, the other side surface of the combination of the resonator 3 and the spacers 32 with respect to the y-axis direction is provided with a connection electrode 34 connected with the electrode 3b of the resonator 3 and extending continuously across the side surface in the height direction (z-axis direction). On the other hand, one side surface of the combination of the resonator 4 and the spacers 41 with respect to the y-axis direction is provided with a connection electrode 43 connected with the electrode 4a of the resonator 4 and extending continuously across the side surface in the height direction (z-axis direction). Similarly, the other side surface of the combination of the resonator 4 and the spacers 42 with respect to the y-axis direction is provided with a connection electrode 44 connected with the electrode 4b of the resonator 4 and extending continuously across the side surface in the height direction (z-axis direction). Specifically, the connection electrodes 33 and 43 disposed close to the base ends of the resonators 3 and 4, respectively, are disposed on the outer side surface of the combination of the resonator 3 and the spacers 31 and the outer side surface of the combination of the resonator 4 and the spacers 41.

The base plate 5 is an insulative plate having the same length as the resonators 3 and 4, and is bendable with respect to a central bending plane (indicated by a dashed line N1 in FIG. 4) in response to acceleration G applied to the acceleration-sensor element 2A. The central bending plane is

positioned at the central portion of the base plate **5** with respect to the thickness direction (y-axis direction) of the base plate **5**. The base plate **5** and each of the resonators **3** and **4** have a gap **5a** therebetween (see FIG. 4) which is given a wider dimension than the range in which the resonator **3** or **4** vibrates in an enclosed manner. In the first preferred embodiment, although the spacers **51** to **54** are attached to the corresponding sides of the base plate **5** and are separated by a predetermined distance in the longitudinal direction of the base plate **5** in order to form the gaps **5a**, the opposite sides of the base plate **5** may alternatively be provided with depressions in place of the spacers. As a further alternative, the base plate **5** and each of the resonators **3** and **4** may have an adhesive layer therebetween having enough thickness for forming gaps.

The spacers **51** and **52** disposed adjacent to the base end have the same length as the spacers **31** and **41** disposed adjacent to the base ends of the respective resonators **3** and **4**. Moreover, the height of the spacers **51** and **52** (in the z-axis direction) is preferably substantially the same as the height  $H_2$  of the base plate **5**. Similarly, the spacers **53** and **54** disposed adjacent to the free end have the same length as the spacers **32** and **42** disposed adjacent to the free ends of the respective resonators **3** and **4**. Moreover, the height of the spacers **53** and **54** (in the z-axis direction) is preferably substantially the same as the height  $H_2$  of the base plate **5**.

The resonators **3** and **4**, the spacers **31**, **32**, **41**, and **42**, the base plate **5**, the spacers **51** to **54** define the acceleration-sensor element **2A** and are composed of materials having the same coefficient of thermal expansion as that of the resonators **3** and **4** (for example, a ceramic material such as PZT). This prevents stress from being generated in the resonators **3** and **4** due to differences in thermal expansion caused by a change in temperature.

One side surface of the base plate **5** having the spacers **51** and **53** attached thereon is provided with an extraction electrode **5b** extending over the entire length of the side surface. The extraction electrode **5b** is connected with an internal electrode **61** extending continuously across the top surface of the base-end portion of the acceleration-sensor element **2A** when the resonators **3** and **4** are in a combined state. On the other hand, an internal electrode **64** extends continuously across a free-end portion of the top surface of the combination of the base plate **5** and the spacers **53**, **54**, **32**, and **42**. The internal electrode **64** functions as a connector for interconnecting the extraction electrode **5b** disposed on one side surface of the base plate **5** with the connection electrodes **34** and **44** disposed on the side surfaces of the respective resonators **3** and **4**.

The two opposite sides of the acceleration-sensor element **2A** with respect to the application direction of acceleration  $G$  are respectively covered with the pair of left and right casing components **6**. Each casing component **6** is preferably substantially U-shaped in cross section, and a projection **6a** disposed adjacent to a first end of the casing component **6** is attached to the base-end portion of one of the opposite side surfaces of the acceleration-sensor element **2A**. On the other hand, a projection **6b** disposed adjacent to a second end of one casing component **6** is attached to a projection **6b** of the other casing component **6** via a spacer **2a** disposed therebetween. The spacer **2a** according to the first preferred embodiment is formed by cutting a longitudinal end-segment of the acceleration-sensor element **2A**, and includes portions of the base plate **5**, the resonators **3** and **4**, and the spacers **53**, **54**, **32**, and **42**. The projections **6a** and **6b** of each casing component **6** have a depression **6c** disposed therebetween, which is a space where the accel-

eration-sensor element **2A** is allowed to bend into. Moreover, each casing component **6** is provided with a stopper **6d** disposed near an inner side of the second-end projection **6b**. The stopper **6d** restricts an over-displacement of the acceleration-sensor element **2A** when a large amount of acceleration  $G$  is applied so as to prevent the acceleration-sensor element **2A** from being deformed or damaging. If the degree of bending of the acceleration-sensor element **2A** is extremely small and the bending spaces can thus be formed based on the thickness of adhesive layers between the casing components **6** and the acceleration-sensor element **2A**, the depressions **6c** and the stoppers **6d** may be omitted.

The inner side surface and the top surface of one casing component **6** are respectively provided with extraction electrodes **62a** and **62b** which are connected with each other, and the inner side surface and the top surface of the other casing component **6** are respectively provided with extraction electrodes **63a** and **63b** which are connected with each other. The casing components **6** are joined with the acceleration-sensor element **2A** via an electrically conductive adhesive for allowing the electrodes **33** and **62a** to be electrically connected with each other, and the electrodes **43** and **63a** to be electrically connected with each other. In this case, an anisotropic electrically-conductive adhesive is used in order to prevent a short circuit between the internal electrode **61**, extending continuously across the base-end portion of the top surface of the combination of the casing components **6** and the acceleration-sensor element **2A**, and an external electrode **71**, and between the electrode **33** and an electrode **4a**.

The extraction electrodes **62b** and **63b** disposed on the top surfaces of the corresponding casing components **6** are aligned with the internal electrode **64** disposed on the free-end portion of the top surface of the acceleration-sensor element **2A**. The electrodes **62b**, **63b**, and **64** are formed after the casing components **6** are attached to the acceleration-sensor element **2A**, and can be fabricated simultaneously by performing, for example, a sputtering process or a deposition process on the top surface of the combination of the casing components **6** and the acceleration-sensor element **2A**. In this case, the internal electrode **61** can also be formed at the same time.

The upper and lower open planes of the combination of the acceleration-sensor element **2A** and the casing components **6** are respectively covered with the pair of upper and lower cover components **7**. The inner surface of each cover component **7** is provided with a cavity-forming recess **7a** for preventing the acceleration-sensor element **2A** from coming into contact with the cover component **7**. A peripheral region surrounding the recess **7a** is attached to one of the open planes. For this reason, a portion of the acceleration-sensor element **2A** to be displaced in response to acceleration  $G$  is completely enclosed by the casing components **6** and the cover components **7**. Similar to the casing components **6**, the cavity-forming recess **7a** in the inner surface of each cover component **7** may be omitted if the cavity can be formed based on the thickness of an adhesive layer provided along the frame region on the inner surface of the cover component **7**.

The outer surface of each cover component **7** is provided with a portion of an external electrode **71** positioned adjacent to the base end of the acceleration-sensor element **2A**, and portions of two external electrodes **72** and **73** positioned close to the free end of the acceleration-sensor element **2A**. Referring to FIG. 1, the two external electrodes **72** and **73** are positioned distant from the external electrode **71** in the longitudinal direction (x-axis direction), and moreover, are

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disposed on two opposite sides from each other in the application direction of acceleration (y-axis direction). The positioning of the two external electrodes 72 and 73 is not limited to that shown in FIG. 1. Alternatively, the external electrodes 72 and 73 may be disposed at an end opposite to the end at which the external electrode 71 is disposed, such that the two electrodes 72 and 73 are disposed on opposite sides in the y-axis direction at that end.

The acceleration sensor 1A having the structure described above has the following conductive path.

Specifically, the upper electrode 3a of the resonator 3 is connected with the external electrode 72 via the connection electrode 33 and the extraction electrodes 62a and 62b. On the other hand, the upper electrode 4a of the resonator 4 is connected with the external electrode 73 via the connection electrode 43 and the extraction electrodes 63a and 63b. The lower electrodes 3b and 4b of the respective resonators 3 and 4 are interconnected with each other via the connection electrodes 34 and 44 and the internal electrode 64, and are connected with the external electrode 71 via the extraction electrode 5b disposed on one side surface of the base plate 5, and the internal electrode 61.

Although only one extraction electrode 5b is provided on one side surface of the base plate 5, two extraction electrodes 5b may alternatively be provided on the two opposite side surfaces of the base plate 5. This may contribute to a further prevention of disconnection of the conductive path.

Accordingly, a surface-mounted-chip acceleration sensor 1A is obtained.

FIG. 6 is a circuit diagram of an example of an acceleration sensor device provided with the acceleration sensor 1A.

Such a sensor device utilizes separate oscillation effects of the acceleration-sensor element 2A. Specifically, the external electrodes 72 and 71 of the acceleration sensor 1A are connected with an oscillation circuit 9a, and the external electrodes 73 and 71 are connected with an oscillation circuit 9b. Each of the oscillation circuits 9a and 9b may be, for example, the commonly known Colpitts oscillation circuit. The resonators 3 and 4 are separately oscillated by the respective oscillation circuits 9a and 9b. The oscillating frequencies  $f_1$  and  $f_2$  are then input to a frequency-difference counter 9c. Subsequently, the frequency-difference counter 9c outputs a signal  $V_o$ , which is proportional to the difference in the frequencies.

When acceleration G is applied to the acceleration sensor 1A, an inertia force acts upon the acceleration-sensor element 2A in a direction opposite to the direction in which the acceleration is applied. This bends the acceleration-sensor element 2A in the opposite direction to the application direction of acceleration G. The bending of the acceleration-sensor element 2A generates stress, thus producing tensile stress in one of the resonators and compressive stress in the other resonator. In the case where resonators of a thickness-shear vibration type are used, the oscillating frequency of the resonator with tensile stress decreases, whereas the oscillating frequency of the resonator with compressive stress increases. Accordingly, the difference in the frequencies is obtained via the external electrodes 71, 72, and 73 so that the signal  $V_o$  proportional to the acceleration G can be obtained.

Using the acceleration sensor 1A in an environment where there is a change in temperature may lead to thermal expansion of the resonators 3 and 4, the base plate 5, the casing components 6, and the cover components 7. If the coefficient of thermal expansion is different among the resonators 3 and 4 and the base plate 5, the acceleration-sensor element 2A may bend when the temperature changes, thus generating stress in the resonators 3 and 4. This means

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that the difference in the frequencies may change due to factors other than acceleration. On the other hand, if the resonators 3 and 4 and the base plate 5 are composed of materials having substantially the same coefficient of thermal expansion, the same amount of stress will be generated in response to a change in temperature. Consequently, the outputs from the two resonators 3 and 4 are received by the frequency-difference counter 9c in a differential manner, such that the changes in the output signals caused by, for example, a change in temperature affecting both resonators 3 and 4 can be counterbalanced. Accordingly, an acceleration sensor device having sensitivity solely against acceleration G can be obtained.

On other hand, even if the coefficient of thermal expansion among the acceleration-sensor element 2A, the casing components 6, and the cover components 7 is different, a temperature change simply does not lead to a generation of stress in the acceleration-sensor element 2A since the acceleration-sensor element 2A is supported by these components only in a cantilever manner.

FIG. 7 illustrates another example of an acceleration sensor device provided with the acceleration sensor 1A.

This acceleration sensor device utilizes a single oscillation effect of the acceleration-sensor element 2A. Specifically, the external electrodes 72 and 73 of the acceleration sensor 1A are connected with a differential impedance sensor circuit 9d, and the external electrode 71, which is a common electrode, is connected with an oscillation circuit 9e. Moreover, reference numerals 9f and 9g indicate matching resistors. In this case, both resonators 3 and 4 are oscillated with the same frequency by the oscillation circuit 9e, so that the phase difference or the oscillation difference can be detected based on the difference in electrical impedance between the resonators 3 and 4. Thus, the output  $V_o$  proportional to acceleration G is obtained via the differential impedance sensor circuit 9d. In order to achieve oscillation with the same frequency, the oscillator circuit 9e may be formed in view of feedback on an output from one of the resonators or a combination of outputs from both resonators.

In this case, like the example shown in FIG. 6, a signal proportional to acceleration G can be obtained while also counterbalancing the changes in the outputs caused by, for example, a change in temperature. Accordingly, an acceleration sensor device having sensitivity that is reactive only to acceleration G can be obtained.

#### Second Preferred Embodiment

FIGS. 8 to 10 illustrate an acceleration sensor according to a second preferred embodiment.

An acceleration sensor 1B is different from the first preferred embodiment in that electrodes 3c and 3d of a resonator 3B and electrodes 4c and 4d of a resonator 4B in a bimorph acceleration-sensor element 2B are disposed on main surfaces which are substantially perpendicular to the application direction of acceleration G. Components equivalent to those in the first preferred embodiment are indicated by the same reference numerals, and descriptions of those components will thus be omitted.

The electrodes 3c and 4c of the respective resonators 3B and 4B are exposed at the outer surfaces of the acceleration-sensor element 2B. On the other hand, the electrodes 3d and 4d face the base plate 5. A first-end portion of the electrode 3c on one surface of the resonator 3B is opposed to a second-end portion of the electrode 3d on the other surface of the resonator 3B at an intermediate portion of the resonator 3B with respect to the longitudinal direction thereof, and similarly, a first-end portion of the electrode 4c on one surface of the resonator 4B is opposed to a second-end

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portion of the electrode **4d** on the other surface of the resonator **4B** at an intermediate portion of the resonator **4B** with respect to the longitudinal direction thereof. On the other hand, second and first-end portions of the respective electrodes **3c** and **3d** do not completely extend to the corresponding ends of the resonator **3B**, and similarly, second and first-end portions of the respective electrodes **4c** and **4d** do not completely extend to the corresponding ends of the resonator **4B**. The resonators **3B** and **4B** preferably have substantially the same height  $H_1$  in the z-axis direction, and preferably have substantially the same thickness  $T_1$  in the y-axis direction. Thus, the resonators **3B** and **4B** have the same resonance frequency when no acceleration is being applied thereto. Since the height  $H_1$  of the resonators **3B** and **4B** is smaller than the height  $H_2$  of the base plate **5** in the z-axis direction, the stress generated in the resonators **3B** and **4B** when acceleration is being applied thereto is greater than in a case where  $H_1=H_2$ .

The vibrating section E in each of the resonators **3B** and **4B** is positioned closer to the fixed end. Specifically, the distance L1 from the vibrating section E to the fixed end is shorter than the distance L2 from the vibrating section E to the free end. Accordingly, an acceleration sensor having high sensitivity, in which signals can be obtained via sections where a large bending stress is generated in response to acceleration G, is provided.

The connection electrodes **33** and **43** disposed close to the base ends of the resonators **3B** and **4B**, respectively, are disposed on the outer side surface of the combination of the resonator **3B** and the spacers **31** and the outer side surface of the combination of the resonator **4B** and the spacers **41**. Thus, the connection electrode **33** is surface-connected with the electrode **3c** of the resonator **3B**, and the connection electrode **34** is surface-connected with the electrode **3d** of the resonator **3B**. Similarly, the connection electrode **43** is surface-connected with the electrode **4c** of the resonator **4B**, and the connection electrode **44** is surface-connected with the electrode **4d** of the resonator **4B**. Accordingly, this ensures the electrical connections among the components.

In the acceleration sensor **1B** according to the second preferred embodiment, the electrodes **3c** and **3d** of the resonator **3B** and the electrodes **4c** and **4d** of the resonator **4B** are not exposed at the upper and lower sides of the acceleration-sensor element **2B**. For this reason, unlike the first preferred embodiment, the electrodes in the second preferred embodiment cannot be trimmed by using, for example, laser, or be coated with, for example, frequency-regulating ink after the casing components **6** are joined with the acceleration-sensor element **2B**. However, since the structure of the second preferred embodiment ensures the connections between the connection electrodes **33** and **34** and the respective electrodes **3c** and **3d** of the resonator **3B**, and the connections between the connection electrodes **43** and **44** and the respective electrodes **4c** and **4d** of the resonator **4B**, an acceleration sensor with a high reliability can be obtained.

#### Third Preferred Embodiment

FIGS. **11** and **12** illustrate an acceleration sensor according to a third preferred embodiment.

An acceleration sensor **1C** is similar to the second preferred embodiment in that electrodes **3e** and **3f** of a resonator **3C** and electrodes **4e** and **4f** of a resonator **4C** in a bimorph acceleration-sensor element **2C** are disposed on main surfaces which are substantially perpendicular to the application direction of acceleration G. On the other hand, the acceleration sensor **1C** is different from the second preferred embodiment in that the height  $H_1$  of the resonators **3C** and

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**4C** is preferably substantially the same as the height  $H_2$  of the base plate **5**. Components equivalent to those in the first and second preferred embodiments are indicated by the same reference numerals, and descriptions of those components will thus be omitted.

Since the height  $H_1$  of the resonators **3C** and **4C** is substantially the same as that of the base plate **5**, unlike the first and second preferred embodiments, the spacers **31** and **32** and the spacers **41** and **42** are omitted. The vibrating section E in each of the resonators **3C** and **4C** is positioned closer to the fixed end. Specifically, the distance L1 from the vibrating section E to the fixed end is shorter than the distance L2 from the vibrating section E to the free end. Accordingly, an acceleration sensor having high sensitivity, in which signals can be obtained via sections where a large bending stress is generated in response to acceleration G, is provided.

In this case, since the electrodes **3e** and **3f** and the electrodes **4e** and **4f** disposed on side surfaces of the acceleration-sensor element **2C** also function as connection electrodes, the fabrication process for the electrodes can be simplified.

The acceleration sensor according to the present invention is not limited to the above-described preferred embodiments.

For example, although the resonators used in the first and second preferred embodiments are of a thickness-shear vibration type, resonators of other alternative vibration types (such as a thickness-extensional vibration type or a longitudinal vibration type) may be used.

Furthermore, although the base plate and each of the first and second resonators in the above-described preferred embodiments have a gap therebetween given a wider dimension than the range in which the resonator vibrates in an enclosed manner, the base plate and each resonator may alternatively be joined with each other in an opposing manner such that the surfaces of the base plate and the resonator are entirely attached to each other. Such an entirely-attached state may cause deterioration of the performance (Q and K) of the resonators since the base plate limits the vibration of the resonators, but is effective in view of the efficiency for generating stress in response to the acceleration.

Although the present invention has been described and illustrated in detail with reference to certain preferred embodiments thereof, it is clearly understood that the same is by way of illustration and example only and is not to be taken by way of limitation, the spirit and scope of the present invention being limited only by the terms of the appended claims.

The invention claimed is:

1. An acceleration sensor comprising:

a base plate; and

first and second resonators each including a piezoelectric material and each having electrodes on two opposite main surfaces thereof, each of the first and second resonators having a vibrating section at an intermediate portion of the resonator with respect to the longitudinal direction thereof; wherein

the first and second resonators are attached to opposite sides of the base plate with respect to a direction in which acceleration is applied so as to define an acceleration-sensor element, only one longitudinal end of the acceleration-sensor element is fixed and the other longitudinal end of the acceleration-sensor element is free such that the first and second resonators bend in the same direction in response to the acceleration, and

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changes in frequency or changes in impedance in the first and second resonators caused by the bending of the acceleration-sensor element are differentially detected in order to detect the acceleration, the acceleration-sensor element is bendable about a central bending plane in response to the acceleration, the central bending plane being positioned at a central portion of the base plate with respect to the application direction of acceleration, and the vibrating section of each of the first and second resonators is disposed closer to the fixed longitudinal end than to the free longitudinal end of the acceleration-sensor element.

2. The acceleration sensor according to claim 1, wherein a height of the first and second resonators in a direction that is substantially perpendicular to the application direction of acceleration is smaller than a height of the base plate in the direction that is substantially perpendicular to the application direction of acceleration.

3. The acceleration sensor according to claim 2, wherein the first and second resonators are attached to the opposite sides of the base plate at positions where the first and second resonators are opposed to each other.

4. The acceleration sensor according to claim 3, wherein each of the first and second resonators is attached to the central portion of the base plate with respect to a height direction of the base plate, the height direction being substantially perpendicular to the application direction of acceleration.

5. The acceleration sensor according to claim 1, wherein the base plate and the first and second resonators are made of at least one material having substantially the same coefficient of thermal expansion.

6. The acceleration sensor according to claim 1, wherein opposite outer surfaces of the acceleration-sensor element are respectively fixedly supported by a pair of casing components at said fixed longitudinal end of the acceleration-sensor element, the outer surfaces being opposite to each

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other with respect to the application direction of acceleration, and open planes defined by the acceleration-sensor element and the casing components are covered with a pair of cover components so that a displacement portion of the acceleration-sensor element, which is bendable in response to the acceleration, is disposed within an enclosed space, one of the electrodes in each of the first and second resonators is disposed at a free-end side of the resonator and is connected with a common electrode via an extraction electrode provided on the base plate, the common electrode being provided at a fixed-end side of an outer surface of a combination of the casing components and the cover components, the other electrode in the first resonator is disposed at a base-end side of the first resonator, said other electrode in the first resonator being connected with a first independent electrode provided at a free-end side of the outer surface of the combination of the casing components and the cover components, said other electrode in the first resonator being connected with the first independent electrode via a first extraction electrode provided on one of the casing components, and the other electrode in the second resonator is disposed at a base-end side of the second resonator, said other electrode in the second resonator being connected with a second independent electrode provided at the free-end side of the outer surface of the combination of the casing components and the cover components, said other electrode in the second resonator being connected with the second independent electrode via a second extraction electrode provided on the other casing component.

7. The acceleration sensor according to claim 6, wherein the casing components are provided with a plurality of internal electrodes disposed on upper surfaces of the casing components, the internal electrodes being connected with the electrodes in each of the first and second resonators.

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